Jet Production at CDF

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1 Introduction

The Run 2 at Tevatron will define a new level of precision for QCD studies in hadron collisions. Both collider experiments, CDF and D0, expect to collect up to 15 fb^{-1} of data in this new run period. The increase in instantaneous luminosity, center-of-mass energy (from 1.8 TeV to 2 TeV) and the improved acceptance of the detectors will allow stringent tests of the Standard Model (SM) predictions in extended regions of jet transverse energy, $E_T^{\rm jet}$, and jet pseudorapidity, $\eta^{\rm jet}$.

In the following, a review of some of the most important QCD results from Run 1 is presented, together with first preliminary Run 2 measurements (based on the very first data collected by the experiment) and future prospects as the integrated luminosity increases.

2 Inclusive Jet Production

The CDF Run 1 inclusive jet cross section measurements [1], performed for jets in the region $0.1 < |\eta^{\rm jet}| < 0.7$ and $E_T^{\rm jet} > 50$ GeV, showed an excess with respect to the NLO calculation in the region $E_T^{\rm jet} > 300$ GeV which initially suggested a possible signal for new physics (see Fig. 1-left). However, a detailed revision of theoretical uncertainties in the NLO calculations indicates that the SM predictions at high-$E_T^{\rm jet}$ suffer from large uncertainties mainly due to the little knowledge of the proton's gluon distribution at high-x. The CTEQ Collaboration showed that it is possible to describe the CDF measurements (see Fig. 1-right) by increasing the amount of gluons in the proton at high-x ($x > 0.3$) without affecting the good description of the rest of the data used in the global fits like, for example, the very precise DIS data. Nowadays, the Tevatron high-$E_T^{\rm jet}$ data, although still has very little statistical power, is being used, together with prompt-photon data from fixed target experiments, to constrain the gluon distribution at high-x.

The new Run 2 data will allow better and more precise jet measurements. The increase in the center-of-mass energy will extend the measured cross sections from $E_T^{\rm jet} \sim 450$ GeV to $E_T^{\rm jet} \sim 600$ GeV, and re-explore possible deviations from the SM predictions. Independent cross section measurements

for forward-forward and central-forward dijet production will be essential to constrain the gluon distribution at high-x and separate an eventual signal for new physics from the current SM uncertainties. Forward jet measurements are not expected to have any contribution from new physics due to the fact that the maximum reachable E_T^{jet} is limited to $E_T^{\mathrm{jet}} \sim 200$ GeV, but have a sensitivity to the proton's gluon distribution similar to that of the central jet measurements.

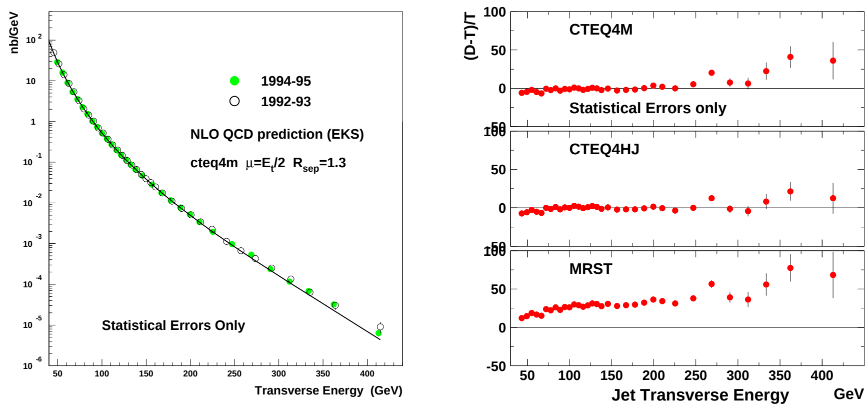

Fig. 1. (Left) Measured inclusive jet cross section as a function of E_T^{jet} for jets in the region $0.1 < |\eta^{\mathrm{jet}}| < 0.7$. The measurement is compared to NLO QCD predictions.(Right) Ratio (Data - Theory)/Theory for the measured jet cross section where different parton density functions are considered in the theoretical predictions.

The CDF Run 1 analyses used the cone algorithm [2] to search for jets, define jet observables and measure jet cross sections. During the past few years different theoretical problems of the cone algorithm were pointed out, namely: the infrared and collinear sensitivity of the defined cross sections and the difficulty to translate the experimental prescription for merging jets to an equivalent procedure at the parton level in theoretical calculations. The longitudinally invariant K_T algorithm [3], initially used in e^+e^- collisions, was proposed for ep and $pp(p\overline{p})$ experiments [4]. It has been already used by the DIS experiments at HERA [5] with so great success that the cone algorithm has been abandoned. Therefore, one of the main goal of the QCD program at Tevatron in Run 2 will be the study of the performance of K_T algorithms in a hadron-hadron environment.

3 Three-jet Production

CDF recently presented a measurement of inclusive three-jet production compared to NLO calculations based on Run 1 data. Jets were searched for using a cone algorithm with radius R=0.7. The events were required to have at least three jets with $E_T^{\rm jet} > 20$ GeV and $|\eta^{\rm jet}| < 2.0$. In order to compare with NLO calculations, additional cuts were applied. The sum of the transverse energy of the jets was required to be above 320 GeV and a cut on the minimum separation between jets of 1.0 unit ($\eta - \phi$ space) was used.

The topology of the three-jet final state was studied using Dalitz variables in the center-of-mass of the three-jet system:

$$X_i = \frac{2 \cdot E_i^{\rm jet}}{M_{\rm 3jets}}, \quad i = 3, 4, 5 \tag{1}$$

where $M_{\rm 3jets}$ denotes the invariant mass of the three jets and the jets are sorted in energy in such a way that $X_3 > X_4 > X_5$, where $X_3 + X_4 + X_5 \equiv 2$. Figure 2-left shows the distribution of the measured three-jet events in the $(X_3 - X_4)$ plane. Different event topologies are observed, including *Mercedes-Benz Star* type of events with $X_3 \sim 0.7$ and $X_4 \sim 0.7$. However, the topologies are dominated by those configurations with a soft third jet where $X_{3,4} \sim 0.95$.

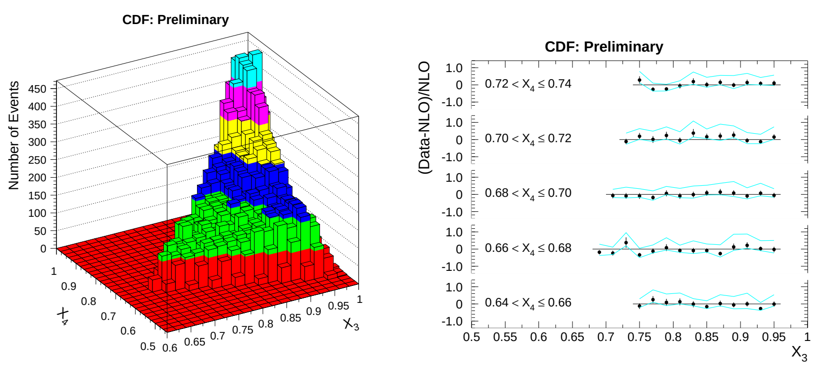

Fig. 2. (Left) Distribution of the measured three-jet events in the $X_3 - X_4$ plane. (Right) Ratio (Data - NLO)/NLO for the differential cross section as a function of X_3 measured in the region $0.64 \le X_4 \le 0.74$.

The differential cross section as a function of X_3, measured in different regions of X_4, was compared to NLO calculations [6]. Figure 2-right shows the comparison between data and theory in the region $0.64 \le X_4 \le 0.74$. Reasonable agreement was observed in the whole $(X_3 - X_4)$ plane. The total measured three-jet production cross section, integrated over the Dalitz plane, was $\sigma^{\rm 3jets} = 466 \pm 2({\rm stat.})^{+206}_{-71}({\rm syst.})$ pb, consistent with the NLO prediction $\sigma^{\rm 3jets}_{\rm NLO} = 402 \pm 3$ pb.

4 Study of Jet Shapes in Run 2

The first 16 pb^{-1} of dijet data collected by CDF in Run 2 were used to measure the jet shapes for jets in the range $30 < E_T^{\rm jet} < 135$ GeV and $|\eta^{\rm jet}| < 2.3$. Jets were searched for using a cone algorithm with R=0.7 starting from the energy deposits in the calorimeter towers, and the jet variables were reconstructed according to the Snowmass convection. The integrated jet shape, $\Psi(r)$, is defined as the average fraction of the transverse energy of jet with lies inside an cone of radius r concentric to the jet cone:

$$\Psi(r) = \frac{1}{N_{\rm jets}} \frac{\sum E_T(0,r)}{E_T^{\rm jet}}, \quad \Psi(r = R) = 1, \tag{2}$$

where the sum runs over the calorimeter towers belonging to the jet.

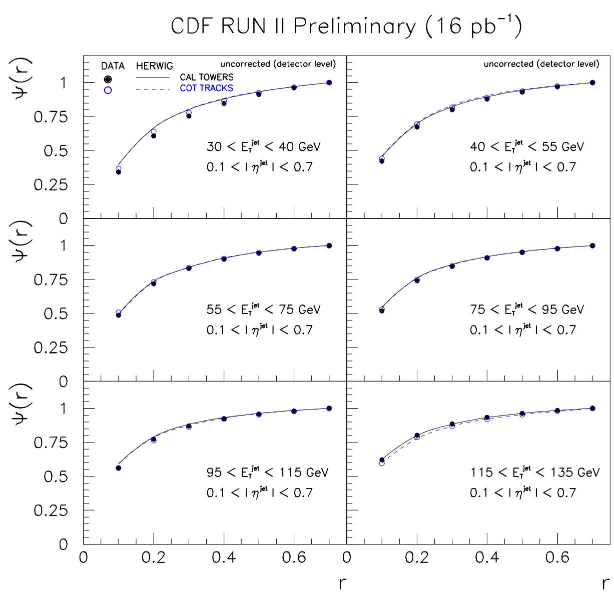

Fig. 3. Measured integrated jet shape, $\Psi(r)$, computed using both calorimeter towers (back dots) and tracks (open circles) for jets in the region $0.1 < |\eta^{\rm jet}| < 0.7$ and $30 < E_T^{\rm jet} < 135$ GeV. The measurements are compared to HERWIG predictions including CDF detector simulation.

In addition, for jet with $0.1 < |\eta^{\rm jet}| < 0.7$, the jet shapes were measured using tracks and a similar expression as Eq. 2 where $E_T^{\rm jet}$ was substituted by the scalar sum of the tracks inside the cone of the jet. Figure 3 shows the

measured jet shapes using both calorimeter towers and tracks compared to the predictions from HERWIG MC [7]. The measurements performed using calorimeter and tracking are in excellent agreement. For a given fixed distance r_0, the measured $\Psi(r = r_0)$ increases with $E_T^{\rm jet}$ indicating that the jets become narrower. The measured jets shapes are well described by the HERWIG MC predictions. Similar studies with b-tagged jets will be necessary to test our knowledge of b-quark jet fragmentation processes in hadronic interactions, which is essential for future precise Top and Higgs measurements.

5 Study of the Underlying Event

The hadronic final states from QCD processes in $p\overline{p}$ collisions at Tevatron are characterized by the presence of soft underlying emissions, usually denoted as *underlying event*, in addition to highly energetic jets coming from the hard interaction. The underlying event contains contributions from initial- and final-state soft gluon radiation, secondary semi-hard partonic interactions and interactions between the proton and anti-proton remnants that cannot be described by perturbation theory. These processes must be approximately modeled using MC programs tuned to describe the data.

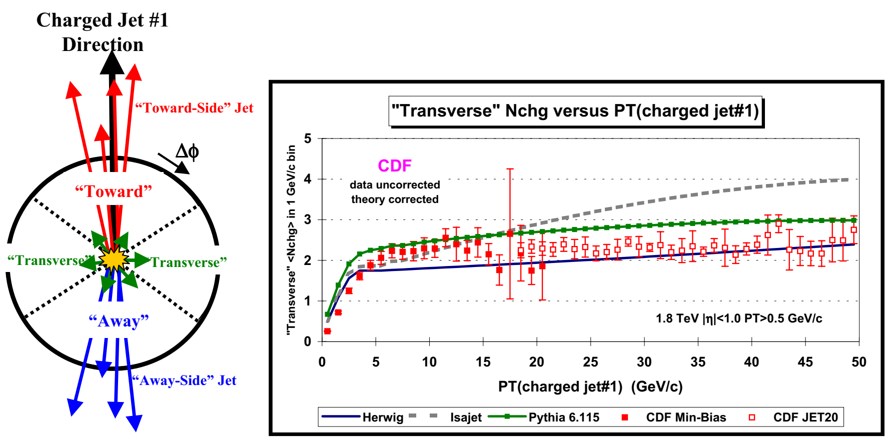

Fig. 4. (Left) Scheme of the different ϕ regions defined around the leading jet. (Right) Measured average track multiplicity in the transverse region as a function of the $P_T^{\rm jet}$ of the leading jet. The measurements are compared to different MC models.

The jet energies measured in the detector contain an underlying event contribution that has to be subtracted in order to compare the measurements to pQCD predictions. Therefore, a proper understanding of this underlying event contribution is crucial to reach the desired precision in the measured jet

cross sections. In the analysis presented here [8], the underlying event in dijet events was studied by looking at regions well separated from the leading jets, where its contribution is expected to dominate the observed hadronic activity. Jets were reconstructed using tracks with $p_T^{\rm track} > 0.5$ GeV and $|\eta^{\rm track}| < 1$ and a cone algorithm (Snowmass convection) with R=0.7 in the $(\eta - \phi)$ space. Jets were sorted in $P_T^{\rm jet}$ and the leading jet defined the direction $\phi = 0$. The ϕ space around the leading jet was divided in three regions: *towards*, *away* and *transverse* (see Fig. 3-left), and the transverse region was assumed to reflect the underlying event contribution. Figure 4-right shows the average track multiplicity in the transverse region as a function of $P_T^{\rm jet}$ of the leading jet. The observed plateau indicates that the underlying event activity is, to a large extend, independent from the hard interaction. Figure 4-right shows the comparison with different MC predictions with default parameters. It becomes clear that the measured track multiplicities provide the necessary input to tune the different parameters of the underlying-event models.

6 Study of W+$N_{\rm jet}$ Production

A detailed study of hard processes involving the associated production of a W boson and a given number of jets in the final state is a main goal of the CDF physics program in Run 2. These processes constitute the biggest background to Top and Higgs production in hadron colliders. Therefore, precise measurements of W+$N_{\rm jets}$ cross sections will be essential to test the NLO QCD calculations used in order to estimate QCD-related backgrounds to Top/Higgs signals.

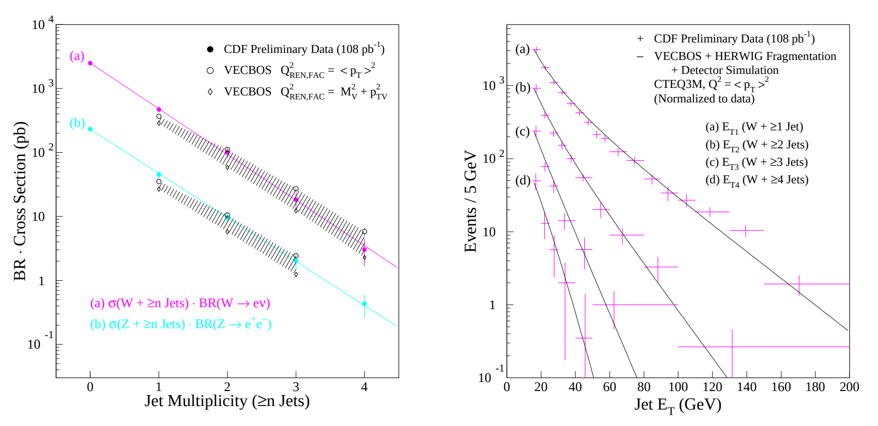

Fig. 5. (Left) Measured W+$N_{\rm jet}$ (and Z+$N_{\rm jet}$) cross sections as a function of jet multiplicity compared to VECBOS predictions. (Right) $E_T^{\rm jet}$ spectrum of the less energetic jet in $W+N_{\rm jet}$ production compared to VECBOS+HERWIG predictions.

In Run 1, CDF measured the cross section for W+$N_{\rm jet}$ production with $N_{\rm jet} \leq 4$ [9]. The measurements were compared to an *enhanced leading-order prediction* based on leading-order calculations (as implemented in VECBOS [10]) interfaced to HERWIG for additional gluon radiation and hadronization, see Fig. 5-left. The measured cross sections were described by the calculations that, however, show a large renormalization scale uncertainty. The $E_T^{\rm jet}$ distribution for the less energetic jet in W+$N_{\rm jet}$ events (see Fig. 5-right) which is sensitive to the additional gluon radiation from HERWIG, was also well described by the enhanced leading-order prediction.

During the last years a number of new Boson+$N_{\rm jet}$ programs have become available [11] which include larger jet multiplicities in the final state, in addition to NLO calculations for the W+dijet case. These different programs are being interfaced to parton-shower models and will make possible precise comparison with Tevatron data as the recorded luminosity of the experiments increases. These measurements will become the testing ground for a future discovery of new particles either at Tevatron or at the LHC.

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